CENTRE NATIONAL D'ÉTUDES SPATIALES

Institut Supérieur de l'Aéronautique et de l'Espace

RÉGION MIDI-PYRÉNÉES

Single Event Effects in 4T and 5T Pinned Photodiode Image Sensors

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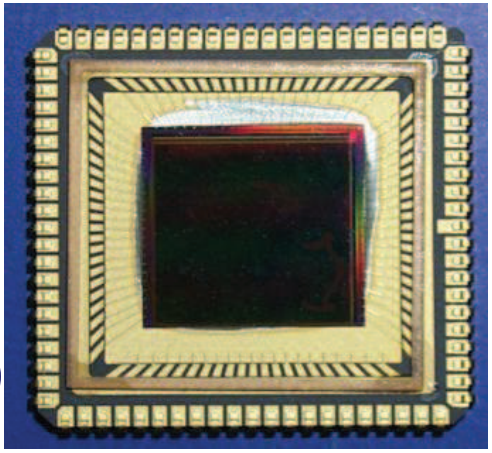
CMOS Image Sensors for High Performance Applications WORKSHOP, Toulouse, Nov. 26-27, 2013

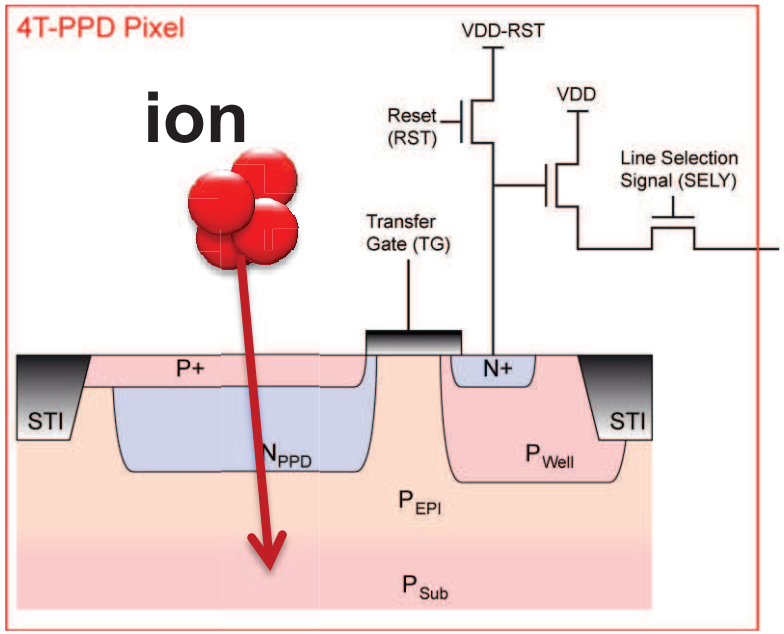
CMOS Image Sensors and radiations

- Image sensors in radiation environment
- Particularly the space imagers, e.g. :
  - Star trackers
  - Scientific imagers (SoloHi, Solar Orbiter …)



- Undergo two classes radiation effects:
  - Cumulative effects (TID, DDD)
  - Single Event Effects (SEE)
    - *Low Linear Energy Transfer (LET)*
    - ***High LET: Heavy Ions***

This study



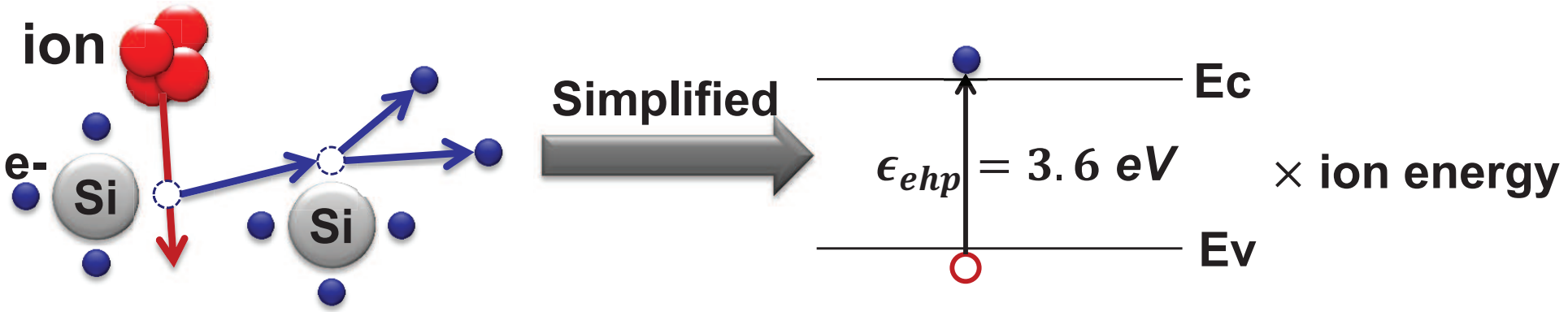
Normal incidence

Radiation effects on electronic devices

- **Ionizing particles : Heavy ions**

M/Q	Ion	Energy (MeV)	Depth (µm in Si)	LET (MeV.cm²/mg)
5	N	60	59	3.3
5	Ne	78	45	6.4
5	Ar	151	40	15.9
5	Kr	305	39	40.4
5	Xe	420	37	67.7

- **Interaction with silicon**
  - **Complex but simplified: Mean energy for pair production**



Radiation effects on electronic devices

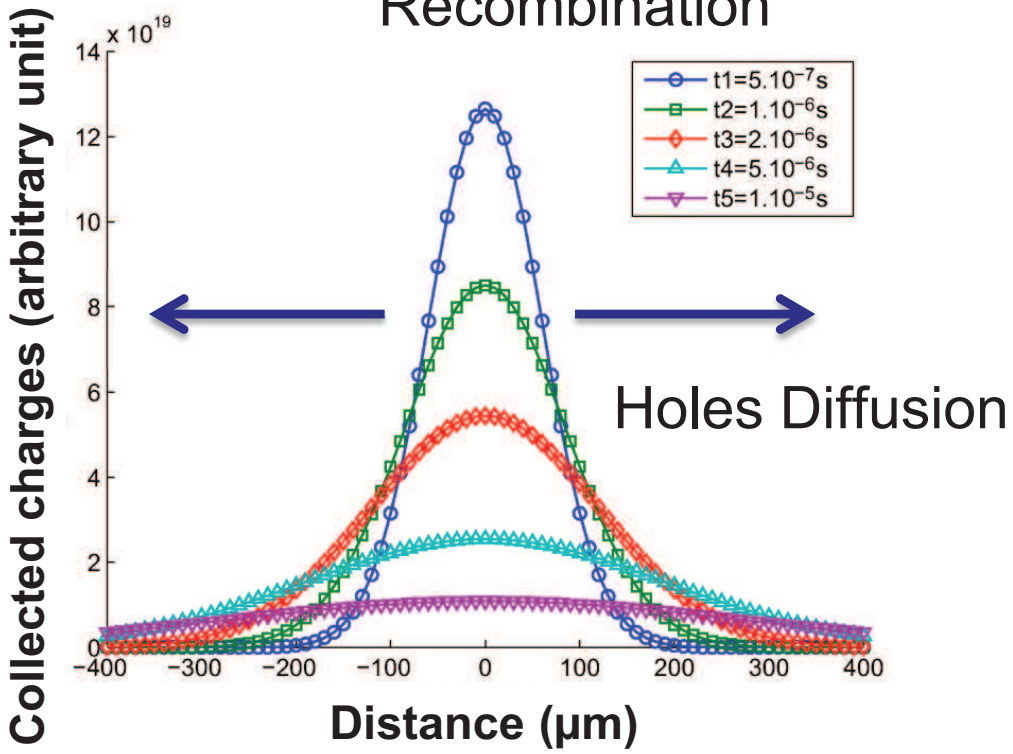
- **Charge cloud in a semiconductor: transport equations**
  - $\frac{\partial n}{\partial t} = G_L - \frac{n-n_0}{\tau_n} + \mu_n \mathrm{div}\left(n\vec{E}\right) + D_n \Delta(n)$
  - $\frac{\partial p}{\partial t} = G_L - \frac{p-p_0}{\tau_p} + \mu_p \mathrm{div}\left(p\vec{E}\right) + D_n \Delta(p)$

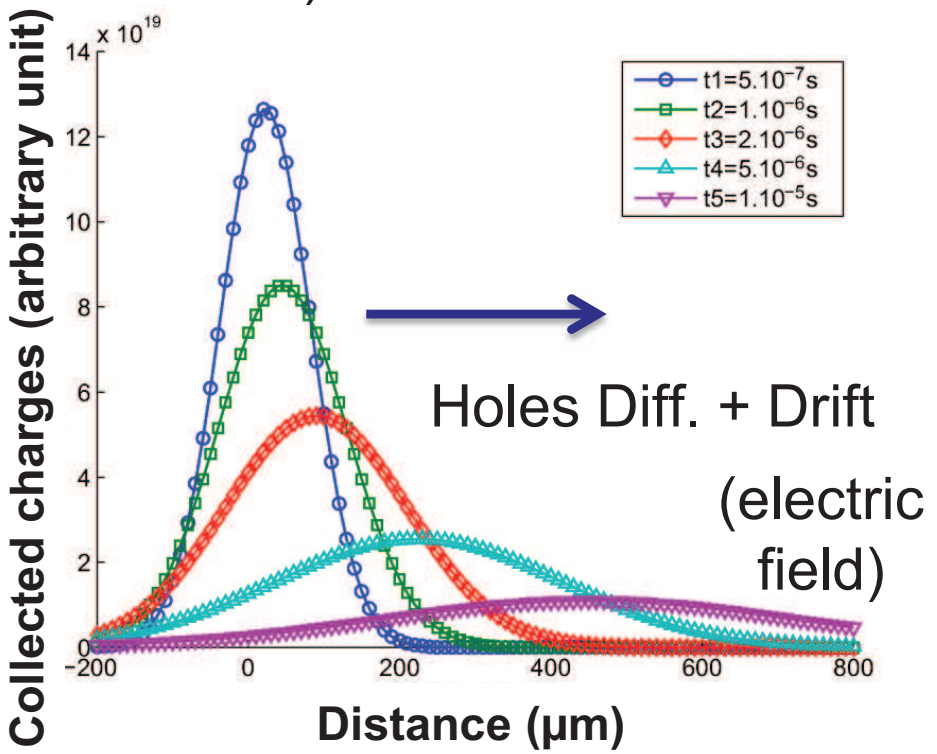
Generation

Recombination

Drift (electric field)

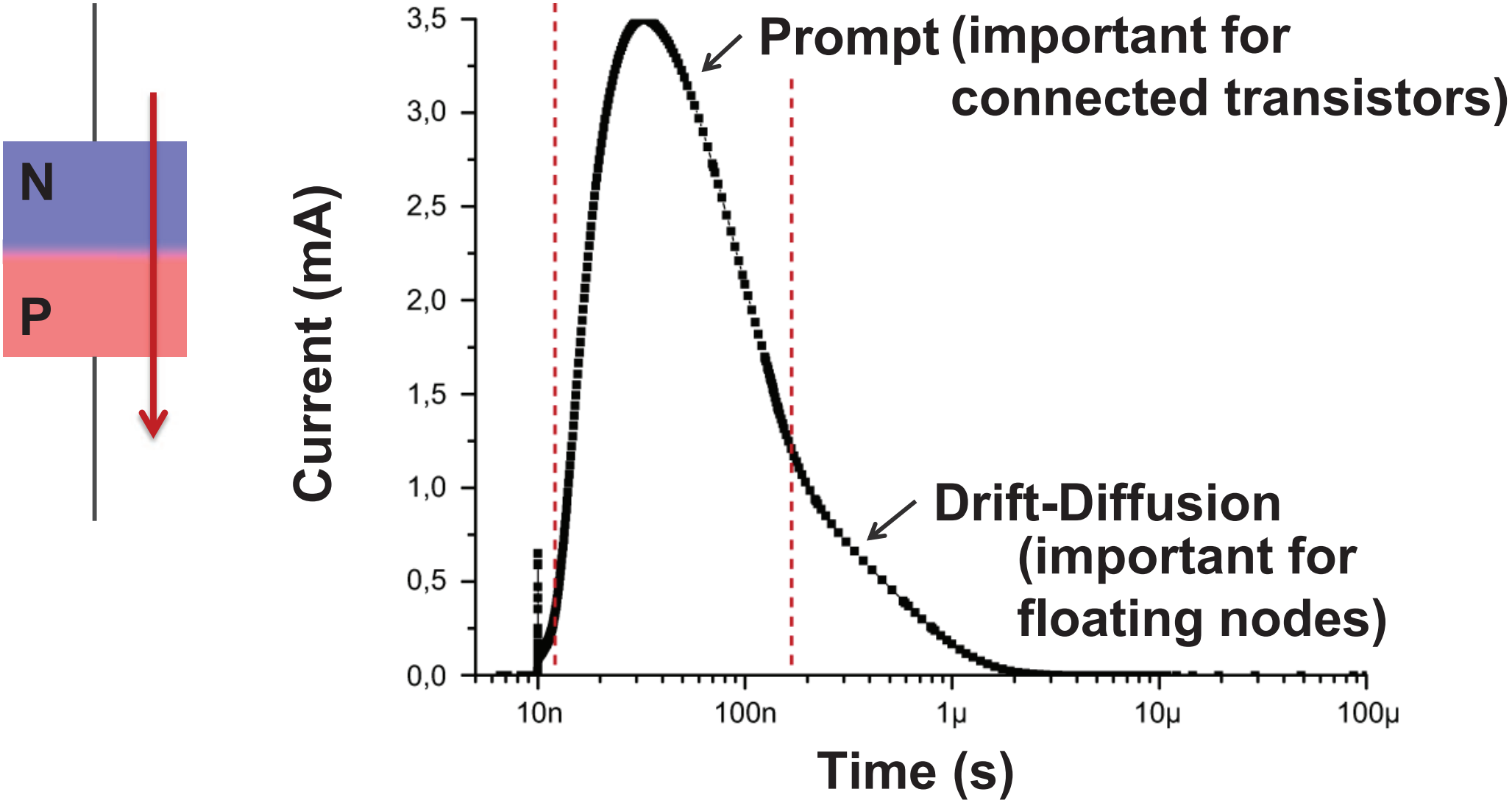
Diffusion





Radiation effects on electronic devices

- Simulated results on a (2D) diode: parasitic current



Single Event Effects

- **Basic**
  - Single Event Transient: analog devices
  - Single Event Upset: digital devices (latch, memories)

- **Triggering of a low-impedance path**
  - Single Event Latchup (parasitic thyristor)
  - Single Event Snapback (parasitic bipolar)

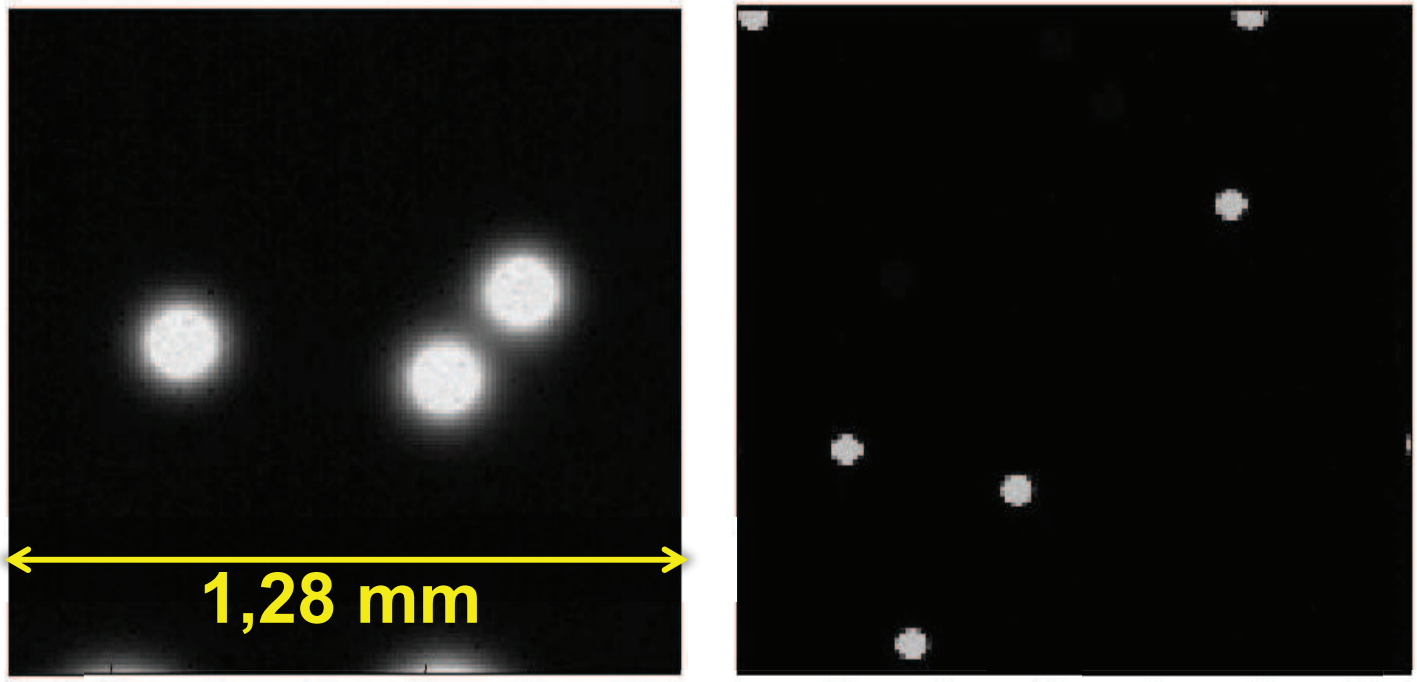
- **Thermal degradation**
  - Single Event Gate Rupture } Thin oxides
  - Single Event Dielectric Rupture } High fields
  - Single Event Burnout → Power devices

Potentially destructive

Motivations

- **In our last study : Single Event Effects (SEE) in 3T pixels**
  - **No functional interruption (no SEL/SES)**
  - **Single Event Transient (SET) effects**
    - *No pixel design dependence*
    - *Bulk or epitaxial substrate dependence*

SETs on 3T pixels Bulk substrate



SETs 3T pixels Epitaxial substrate

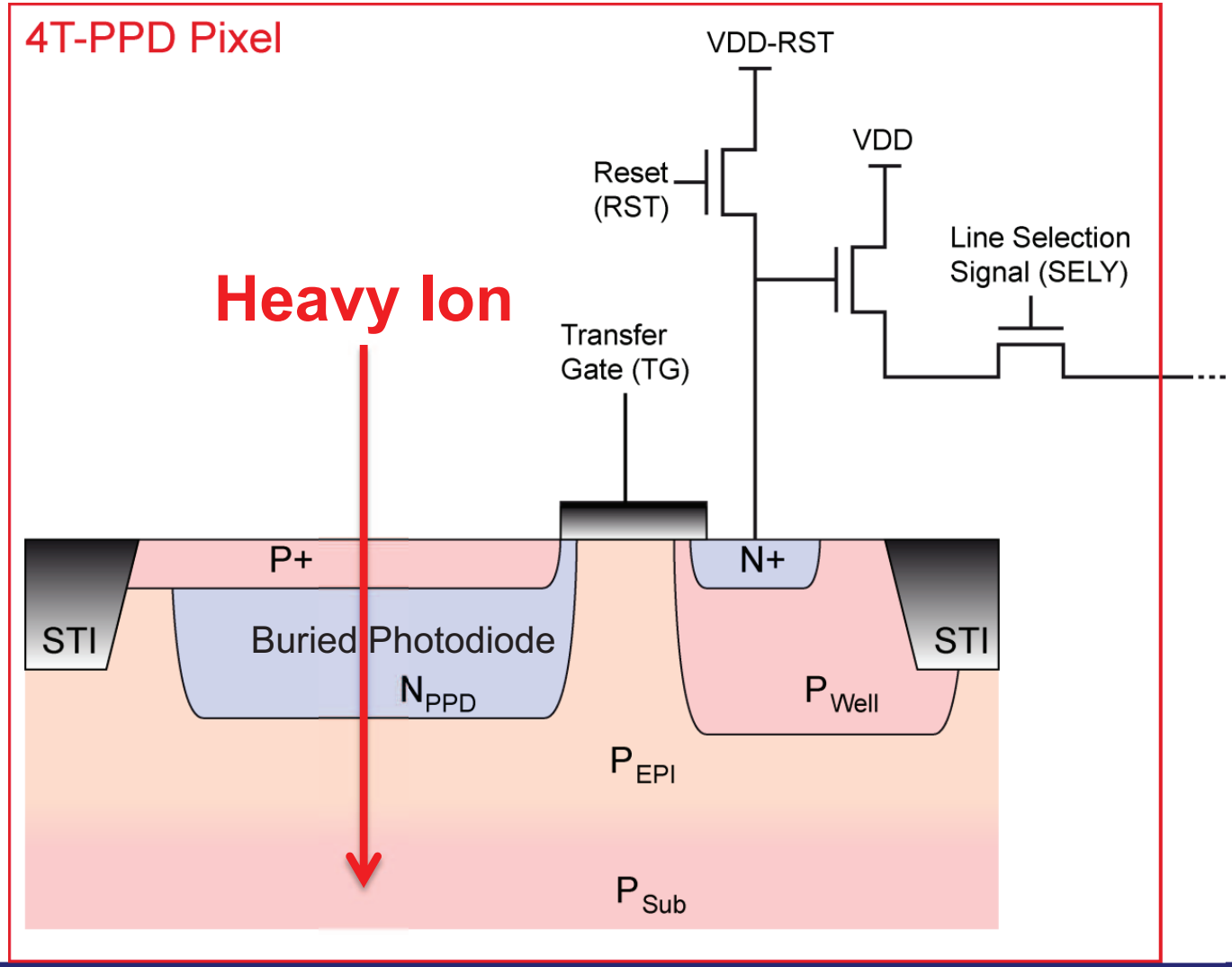
What about 4T pixels based on Pinned PhotoDiode (PPD) ?

Specificities of 4T-Pixels with PPD

- Standard CMOS technology for circuits
- Dedicated implants for Pinned PhotoDiodes (PPD)

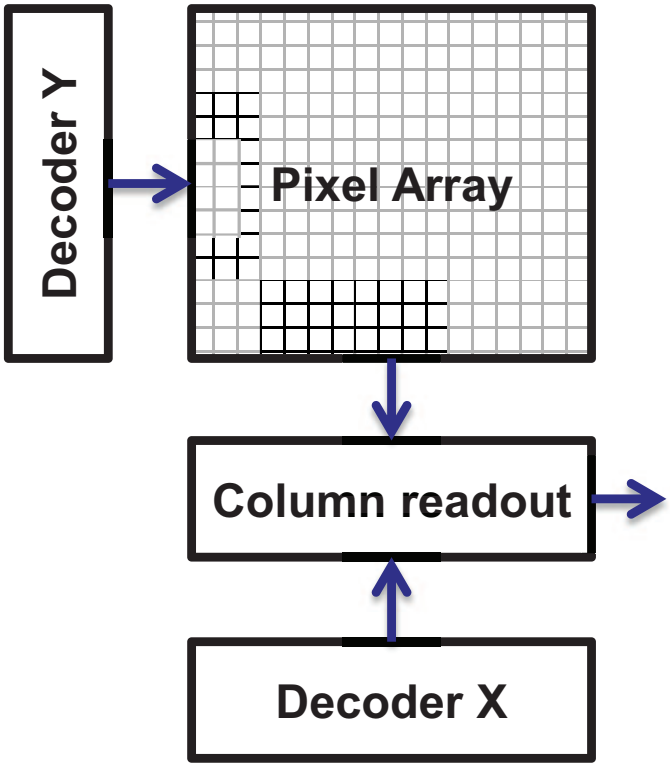
- 4T and 3T are different structures

- Yet, few SEE studies on 4T-PPD CIS



Experimental setup

- "Basic" devices tested
  - Pixels
  - Address decoders (row and column)
  - Column readout circuits



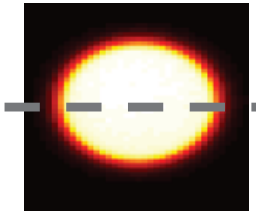
- No on-chip "advanced" functions
  - No on-chip sequencer
  - No Analog to Digital converters

→ Only SEE specific to CIS

- Two sensors irradiated
  - CMOS Image Sensor A → Foundry A
  - CMOS Image Sensor B → Foundry B

First effect: Single Event Transient

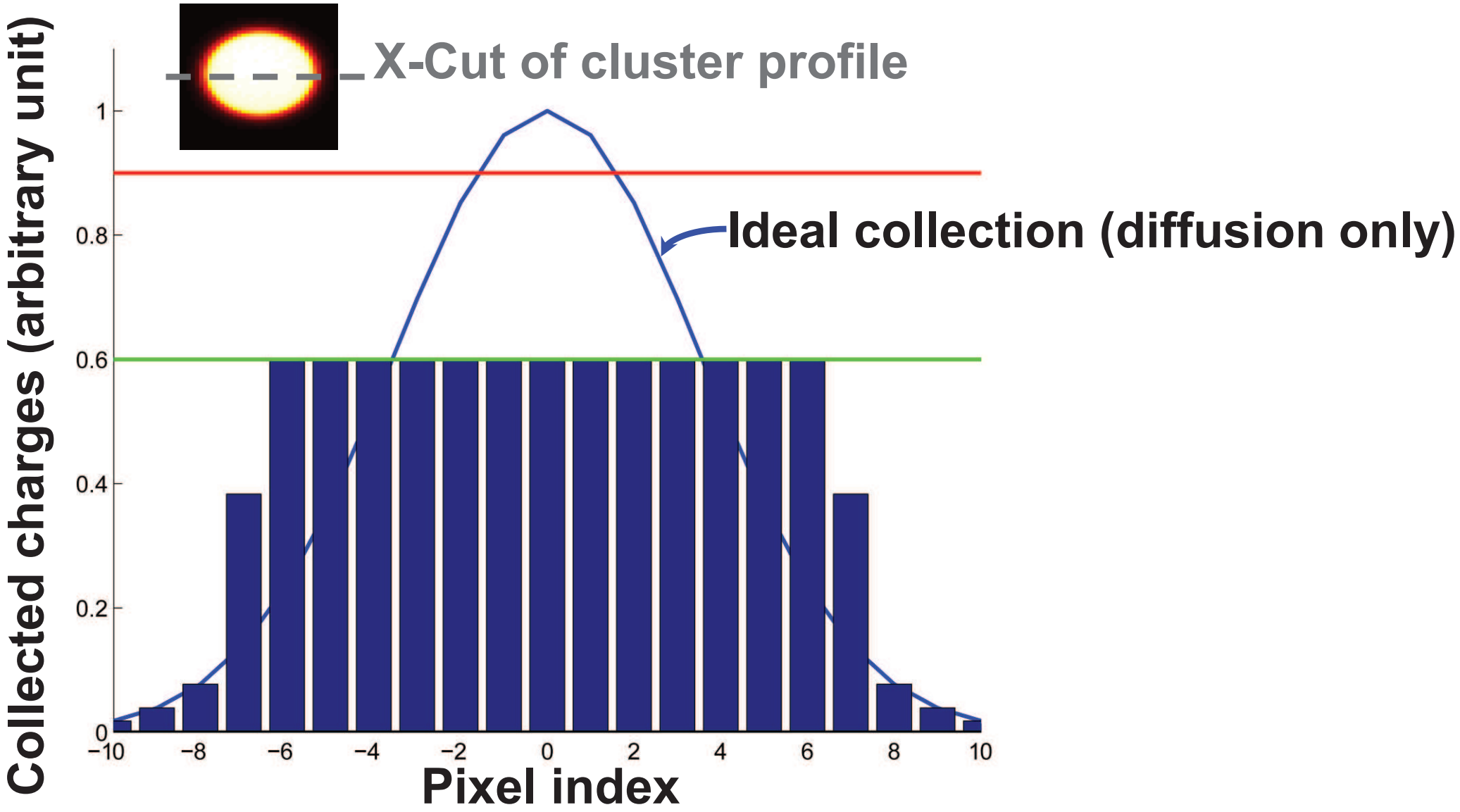
- **PPD has the lower saturation level**



X-Cut of cluster profile

First effect: Single Event Transient

- PPD has the lower saturation level



First effect: Single Event Transient

- PPD has the lower saturation level

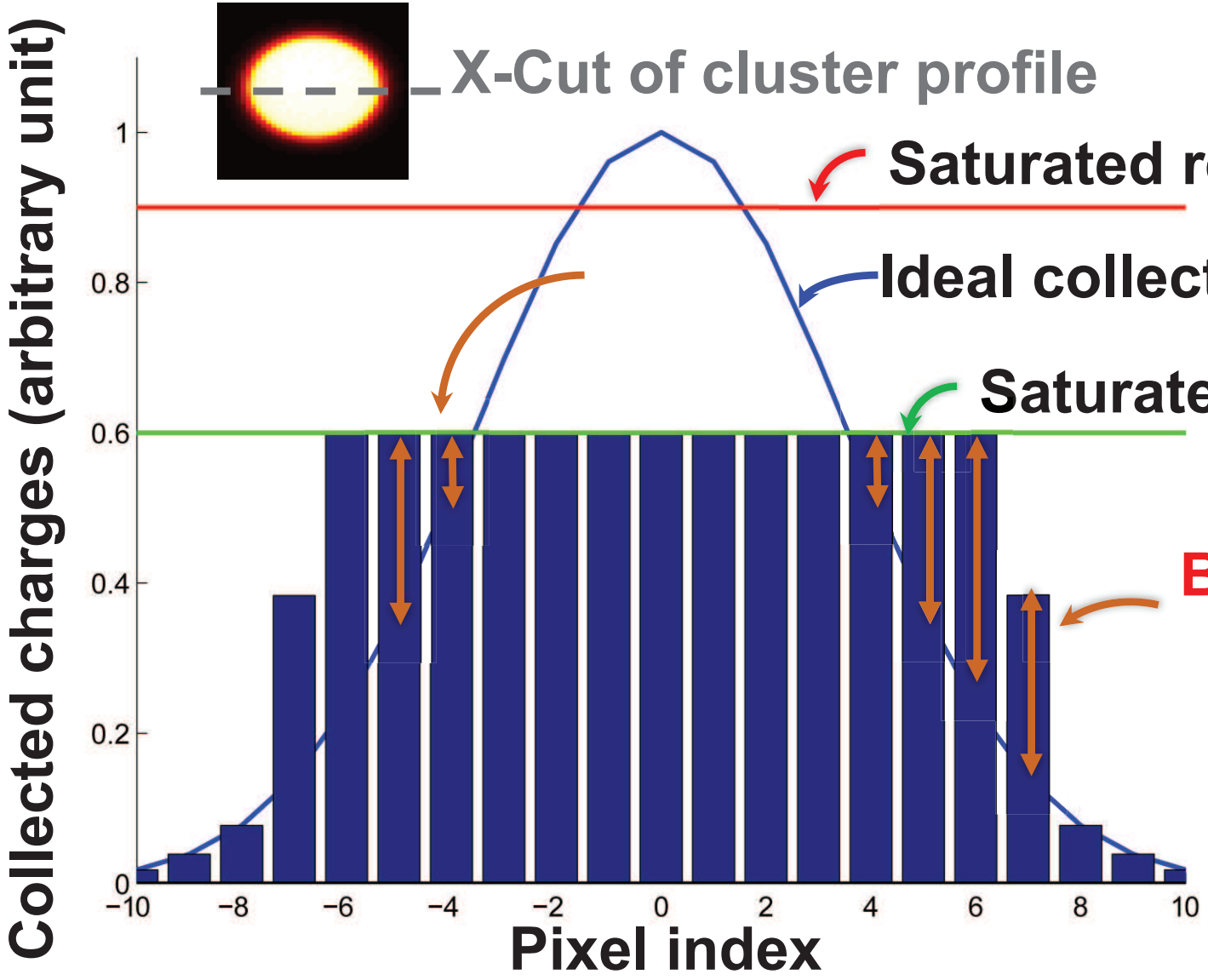
X-Cut of cluster profile

Saturated readout circuit level

Ideal collection (diffusion only)

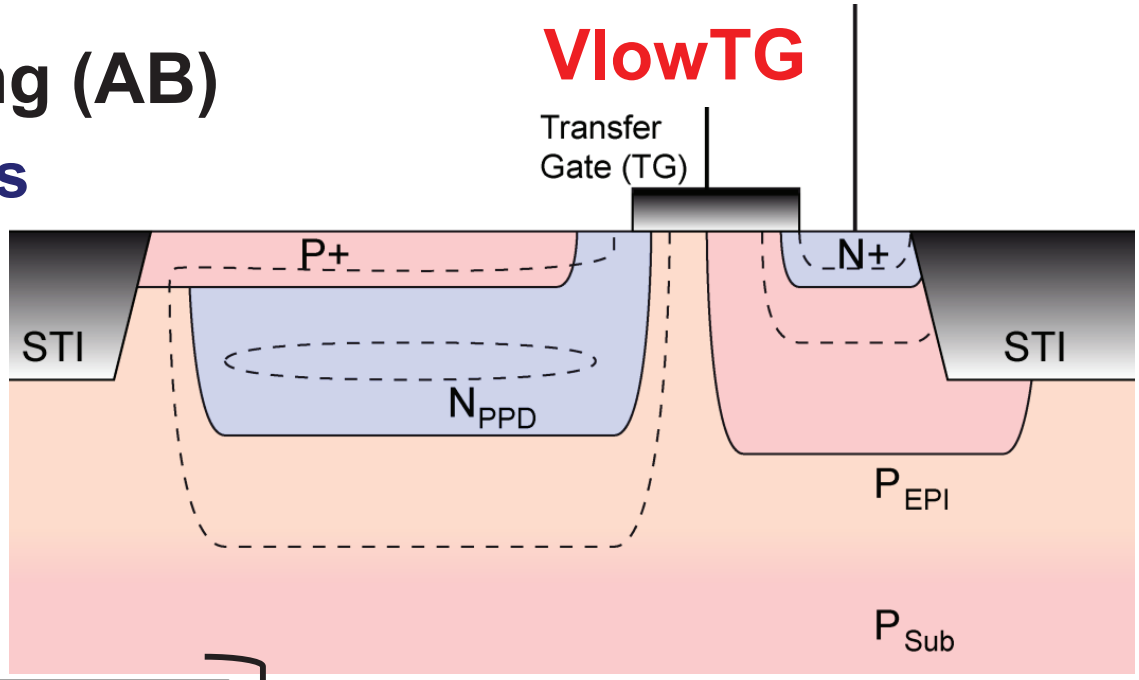
Saturated photodiode level

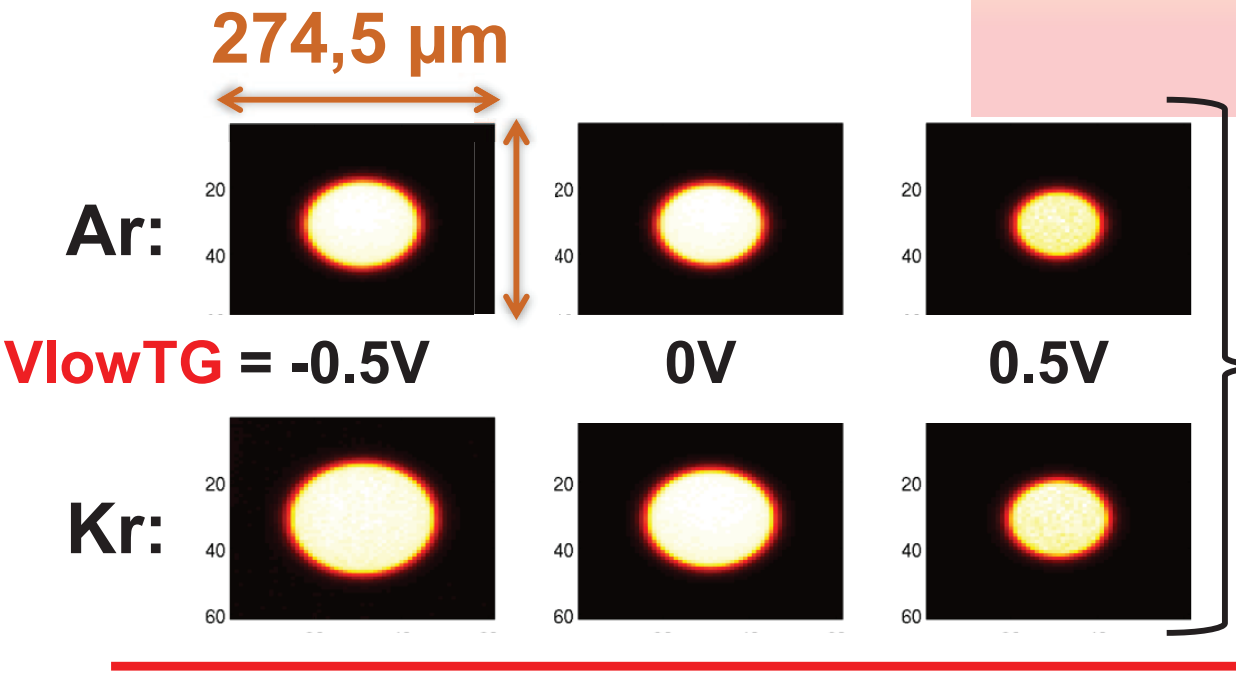
Blooming is visible on the output !



SETs – Variation with anti-blooming

- **Effect of the Anti-Blooming (AB)**
  - **Using 2 different methods**
  - **With variation of the AB level**



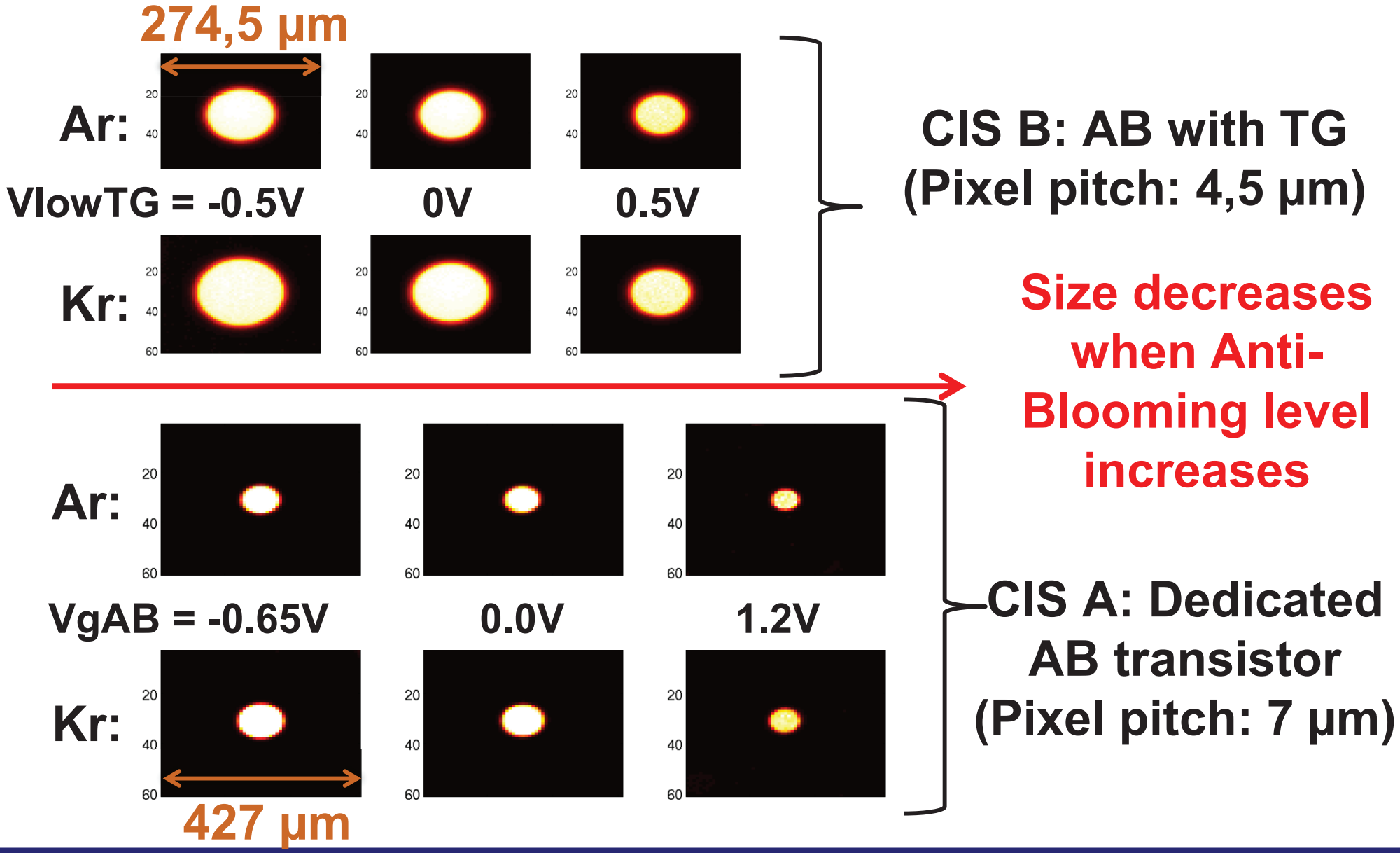


CIS B: AB with TG (Pixel pitch: 4,5 µm)

SET Area decreases when AB level increases

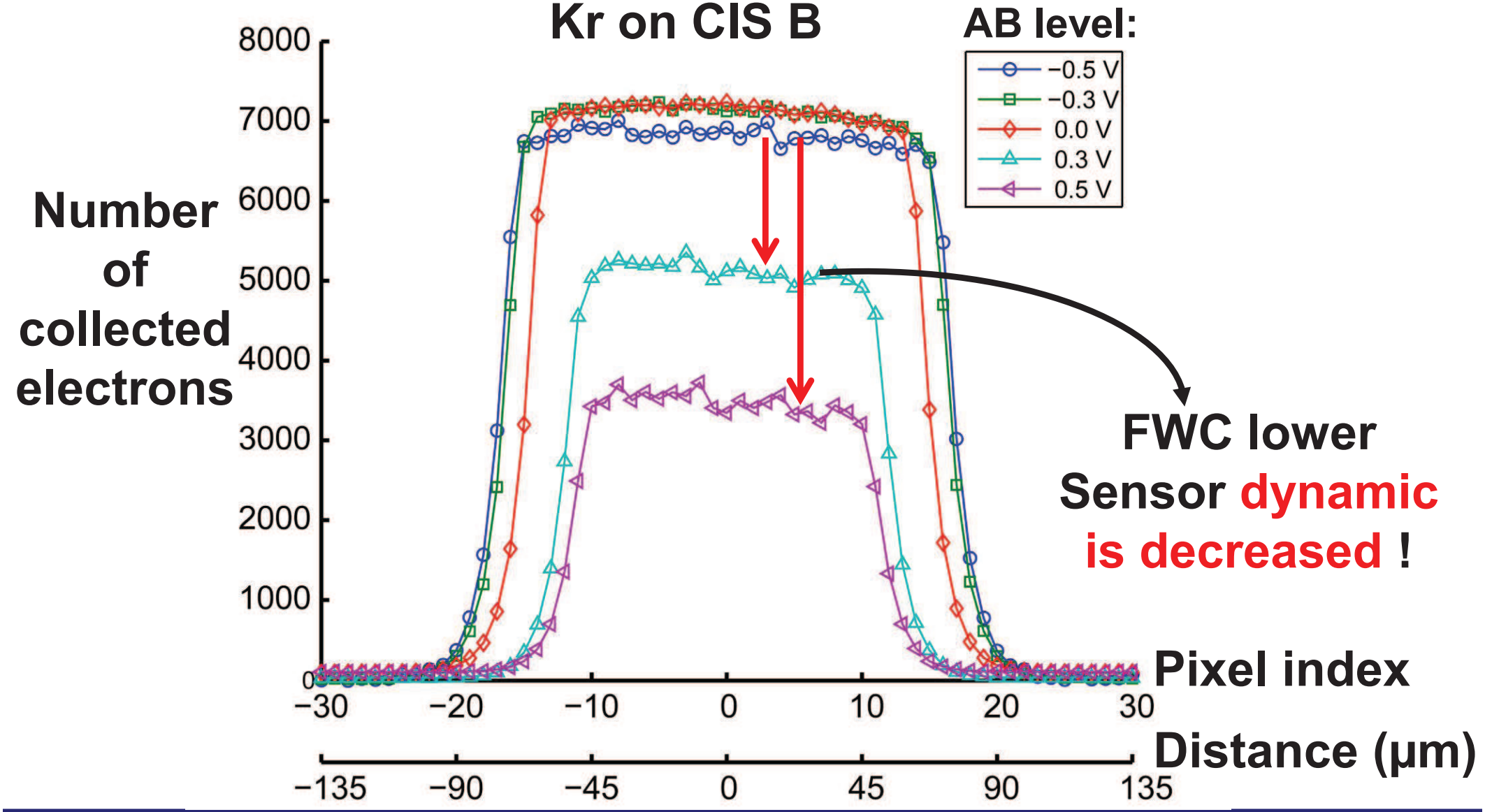
SETs – Variation with anti-blooming

- Effect of the Anti-Blooming (AB) for 2 different methods



SETs – Anti-Blooming drawback

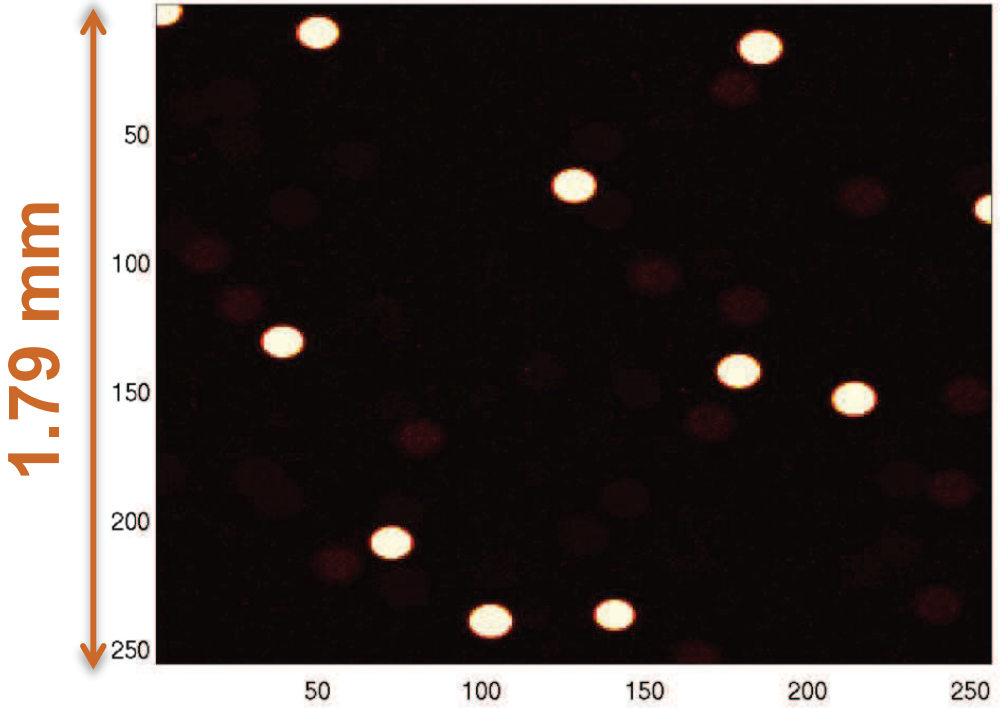
- **Decrease the Full Well Capacity of the photodiode**



Second effect : “black” row and injection

- Two CIS exposed to the ion flux

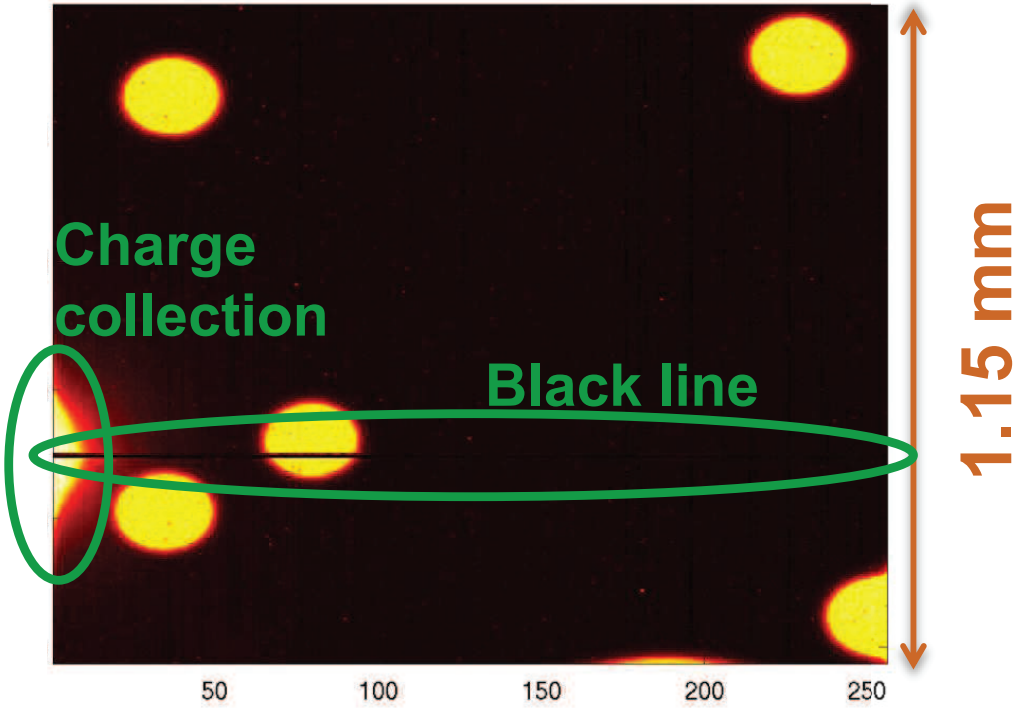
- Foundry A



Xe on CIS A (Higher LET)

No functional problem

- Foundry B



Kr on CIS B

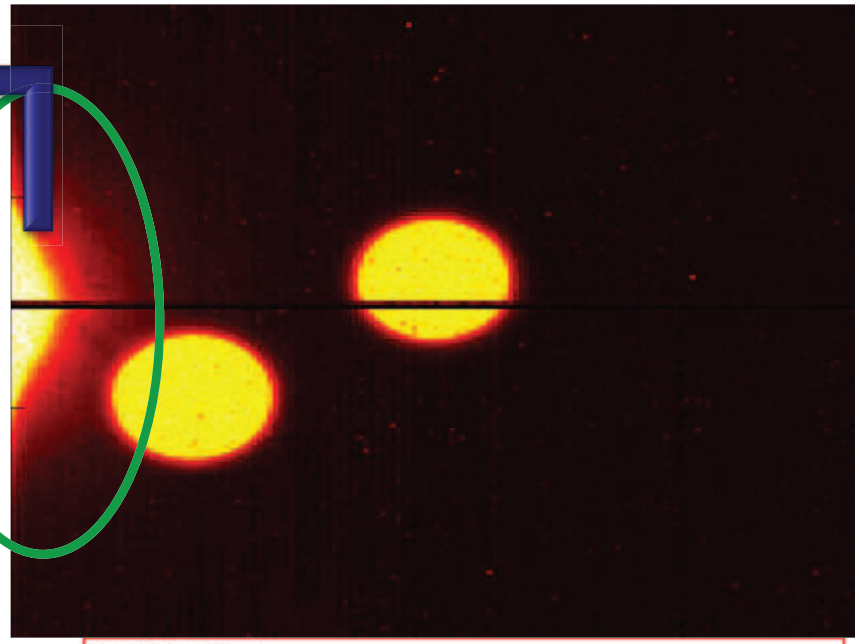
Random functional problems until reset

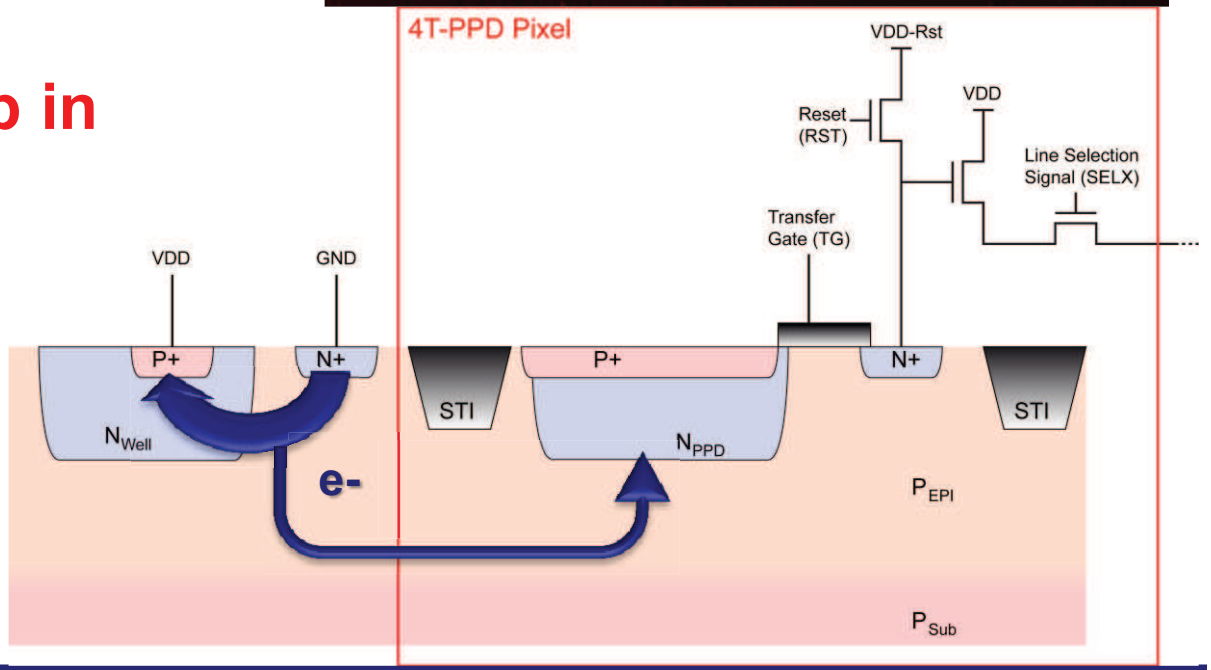
Second effect : “black” row and injection

- Collection of carriers
  - Nothing in MOSFET normal operation (image in dark)
  - Hot carriers on the left part of the circuit

Single Event Latchup in address decoder

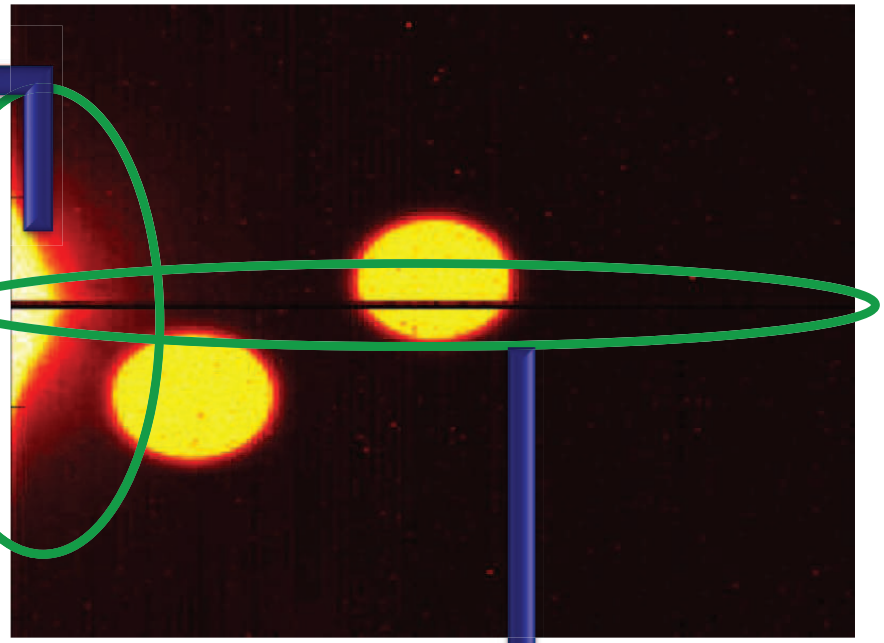
Not linked to 4T pixels !





Second effect : “black” row and injection

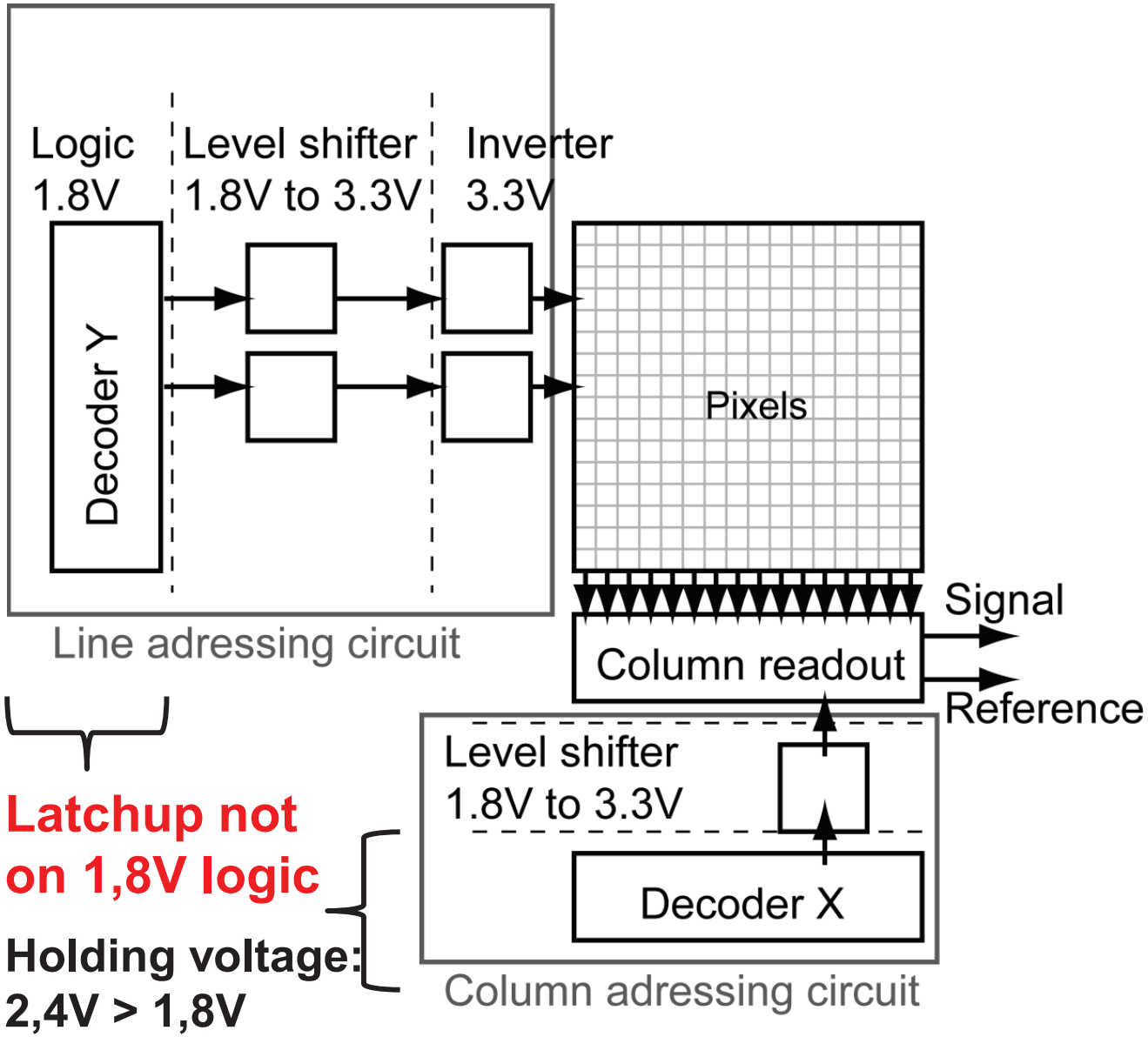
- Collection of carriers
  - Nothing in MOSFET normal operation (image in dark)
  - Hot carriers on the left part of the circuit



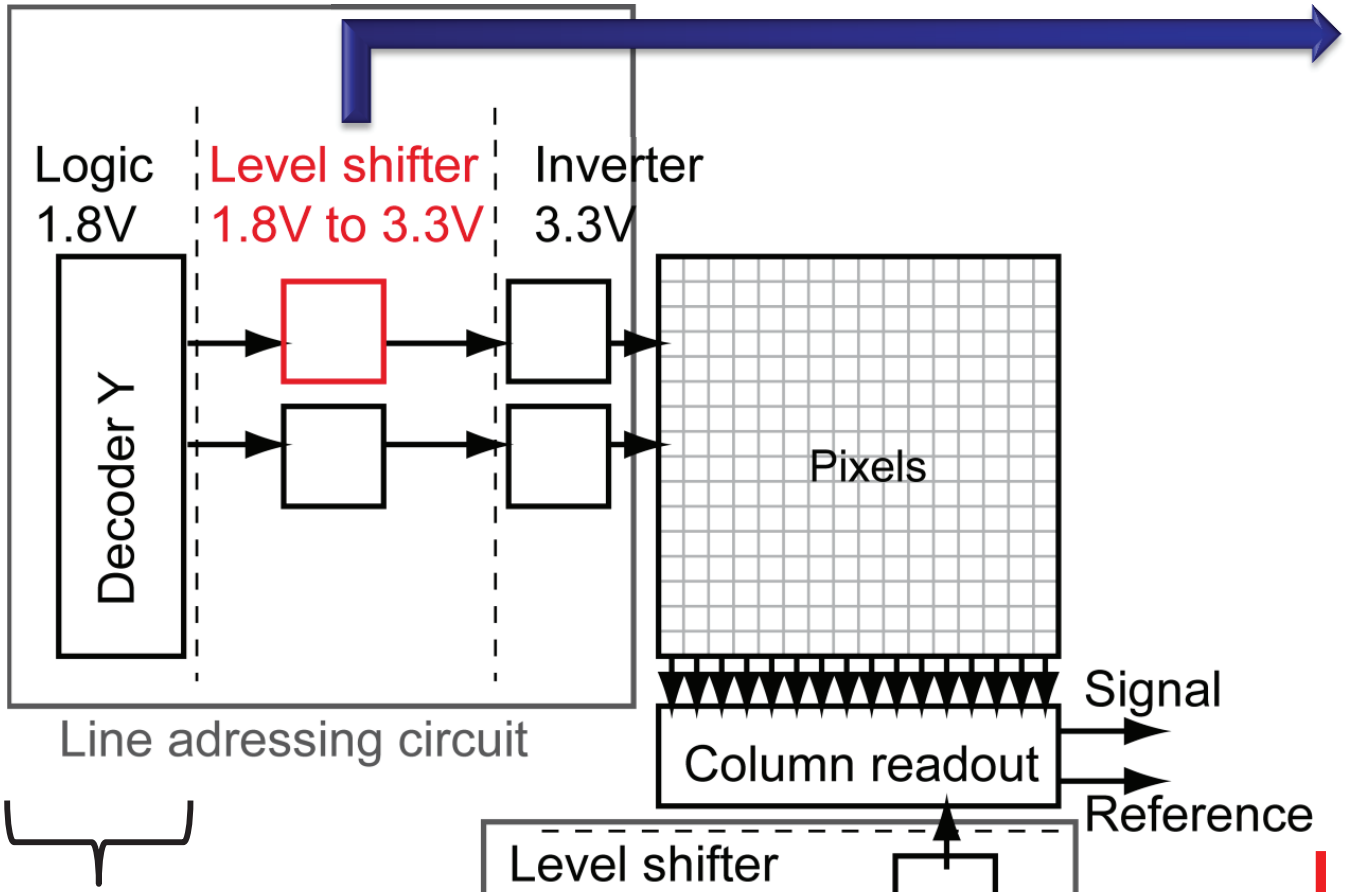
Single Event Latchup in address decoder

- Black rows
  - Selection signal is wrong
  - Address decoder is no longer fully functional

Single Event Latchup: localization

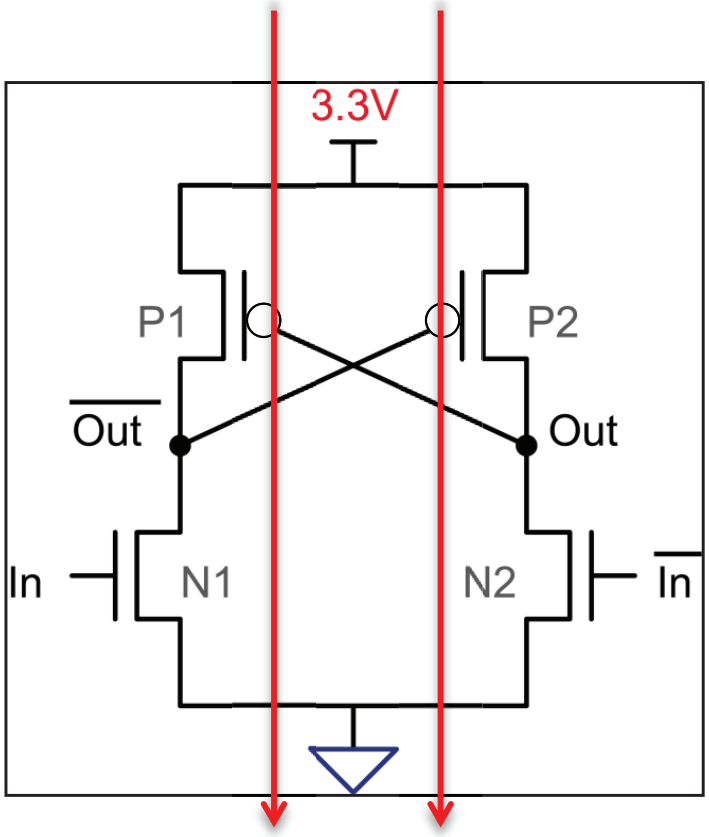


Single Event Latchup: localization

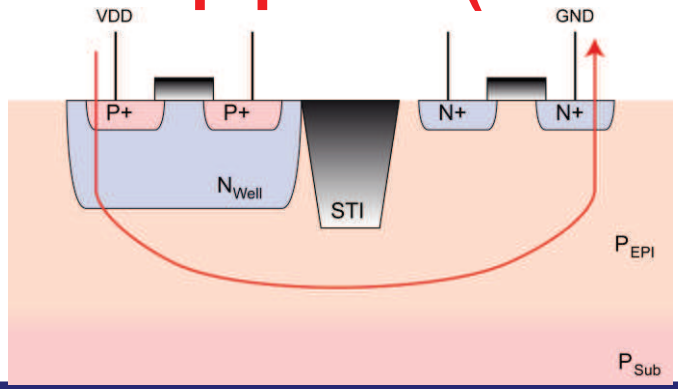


Latchup not on 1,8V logic

Holding voltage: 2,4V > 1,8V



Latchup paths (PNPN)

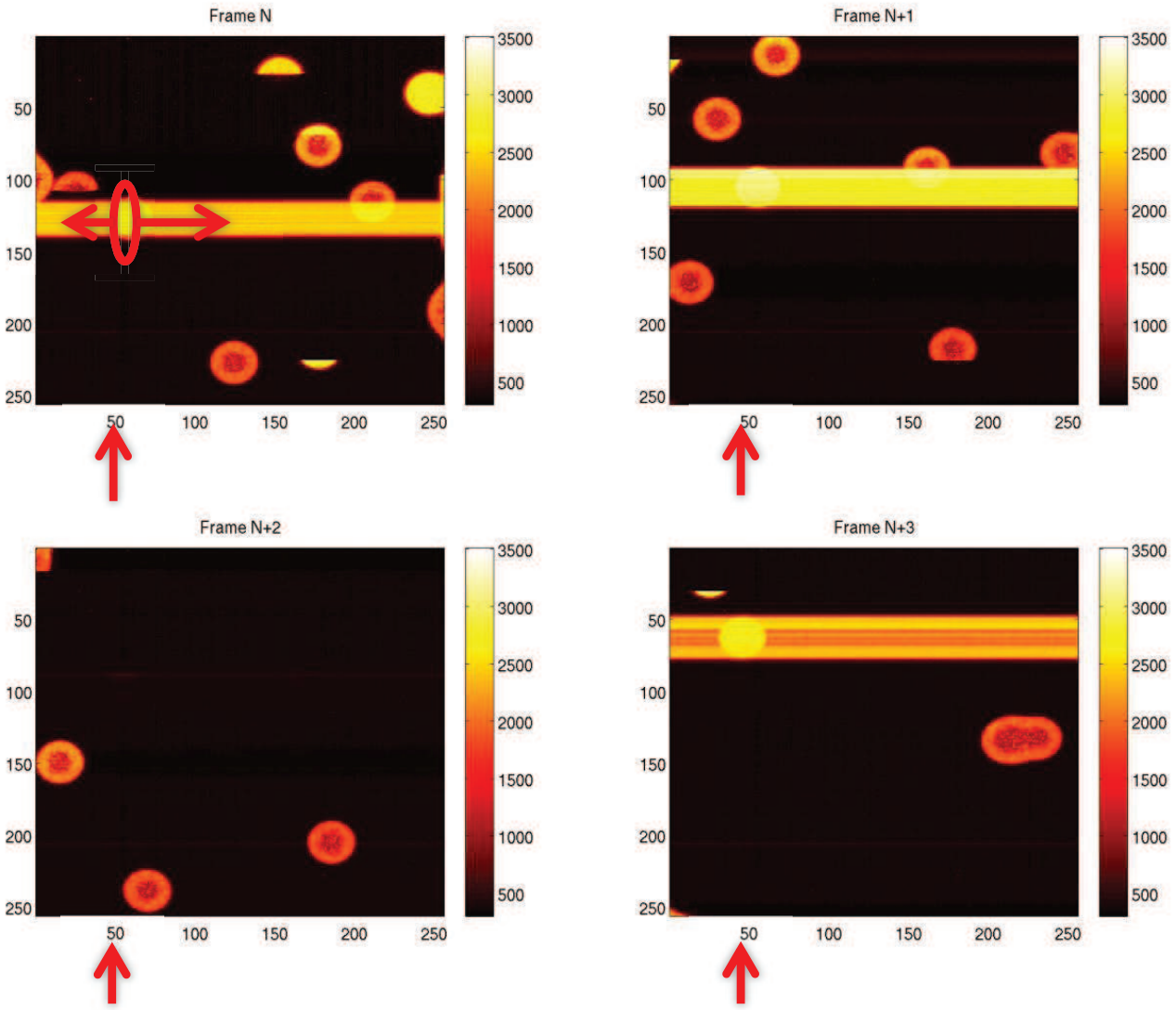


Third effect : Bands

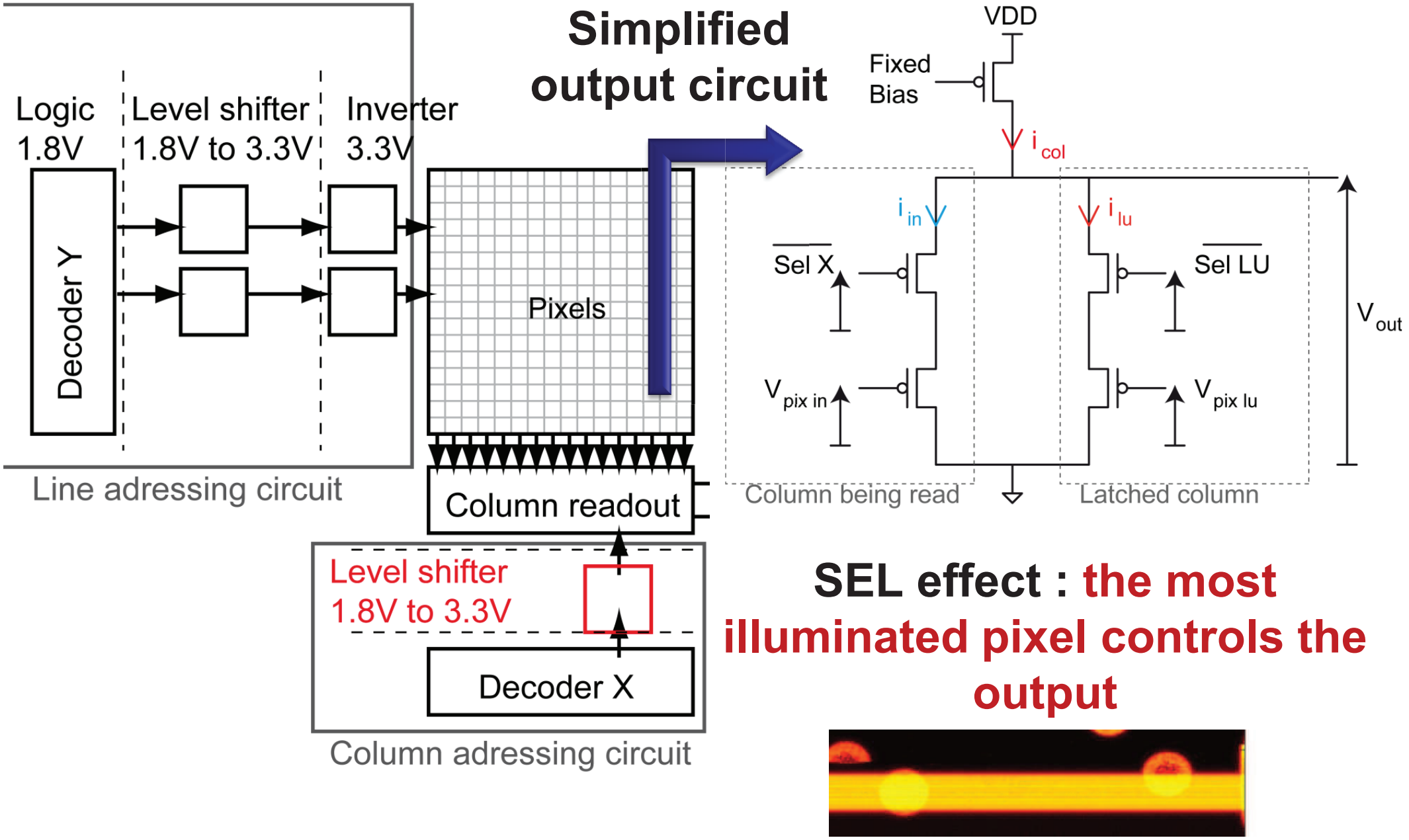
- Illuminated bands starting randomly during irradiation

- Always involves a SET on the same column (50 here)

- Band effect disappear only when power is reset



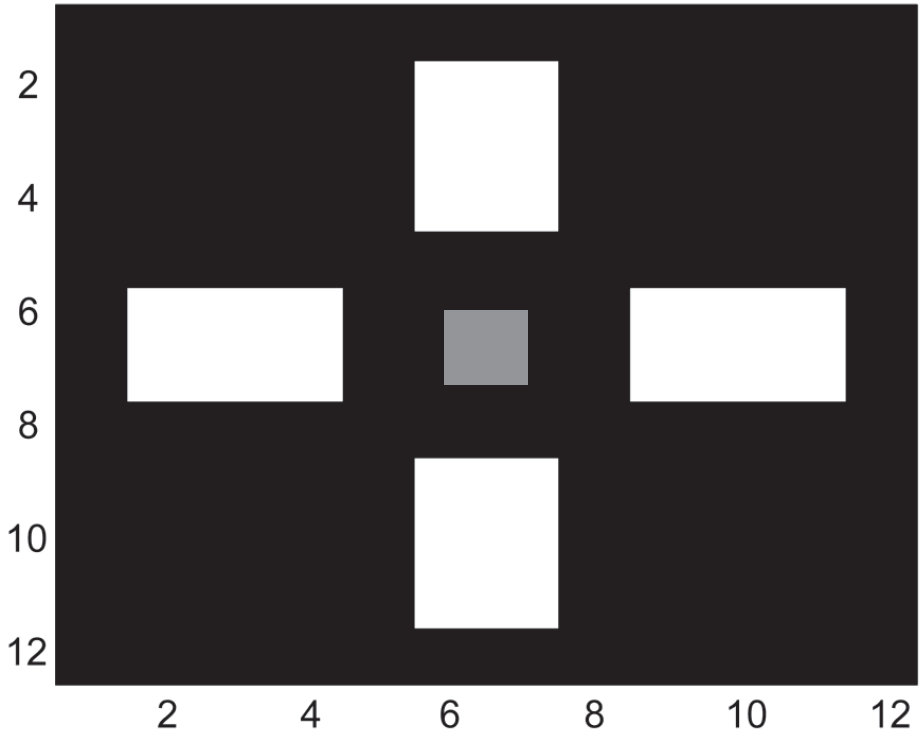
Single Event Latchup: localization



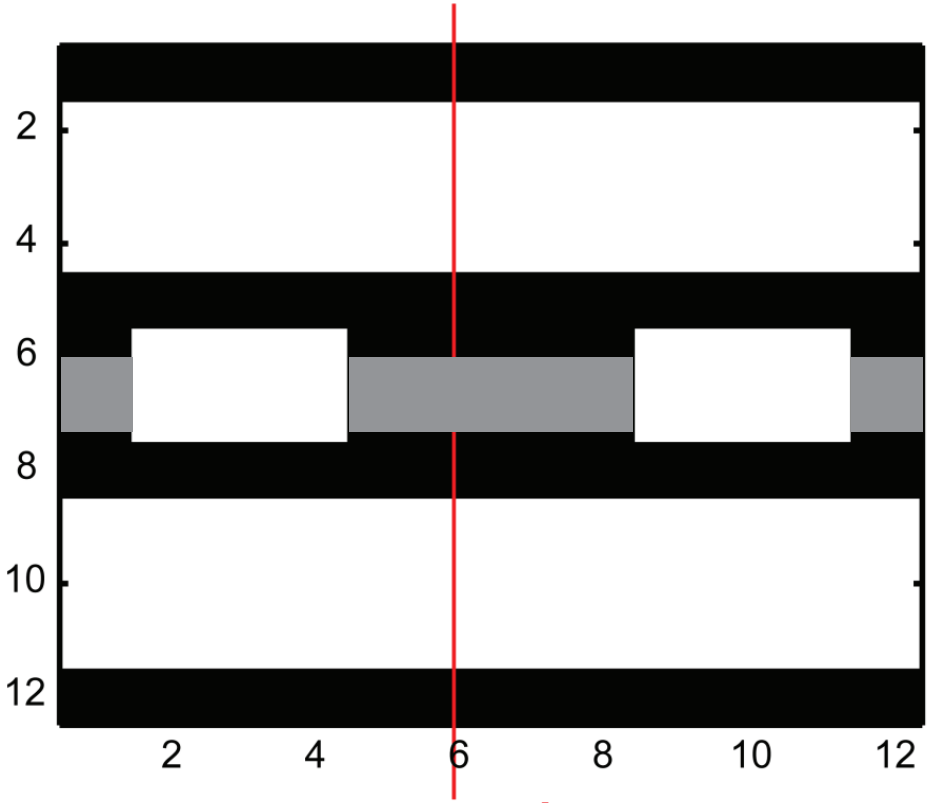
SEL effect : the most illuminated pixel controls the output

Effect of Latchup on columns

- Frames are no longer the real image
- Example: In the case of an illuminated pattern



Non Latched



Latched on 6th column

Pattern cannot be recognized !

Conclusion

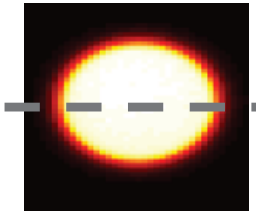
- Single Event Latchup
- Functional interrupts
  - Until reset of power
- Black rows / hot carriers
- Column always connected
- Effects stack !
- Mitigation :
  - Operational: low supply
  - Design: Guard rings, P and NMOST distance
  - Process: thin epi. layer

- Single Event Transient
- Frame perturbation
  - One frame, several frames when sensor has lag
- Pixel collecting charges (diffusion and blooming)
- Mitigation :
  - Anti-blooming
    - *Two methods used here*
  - Diffusion
    - *Thinner epitaxial Layer*

Thank you !

Single Event Transient effects

- 1st case: lower saturation level due to readout circuits



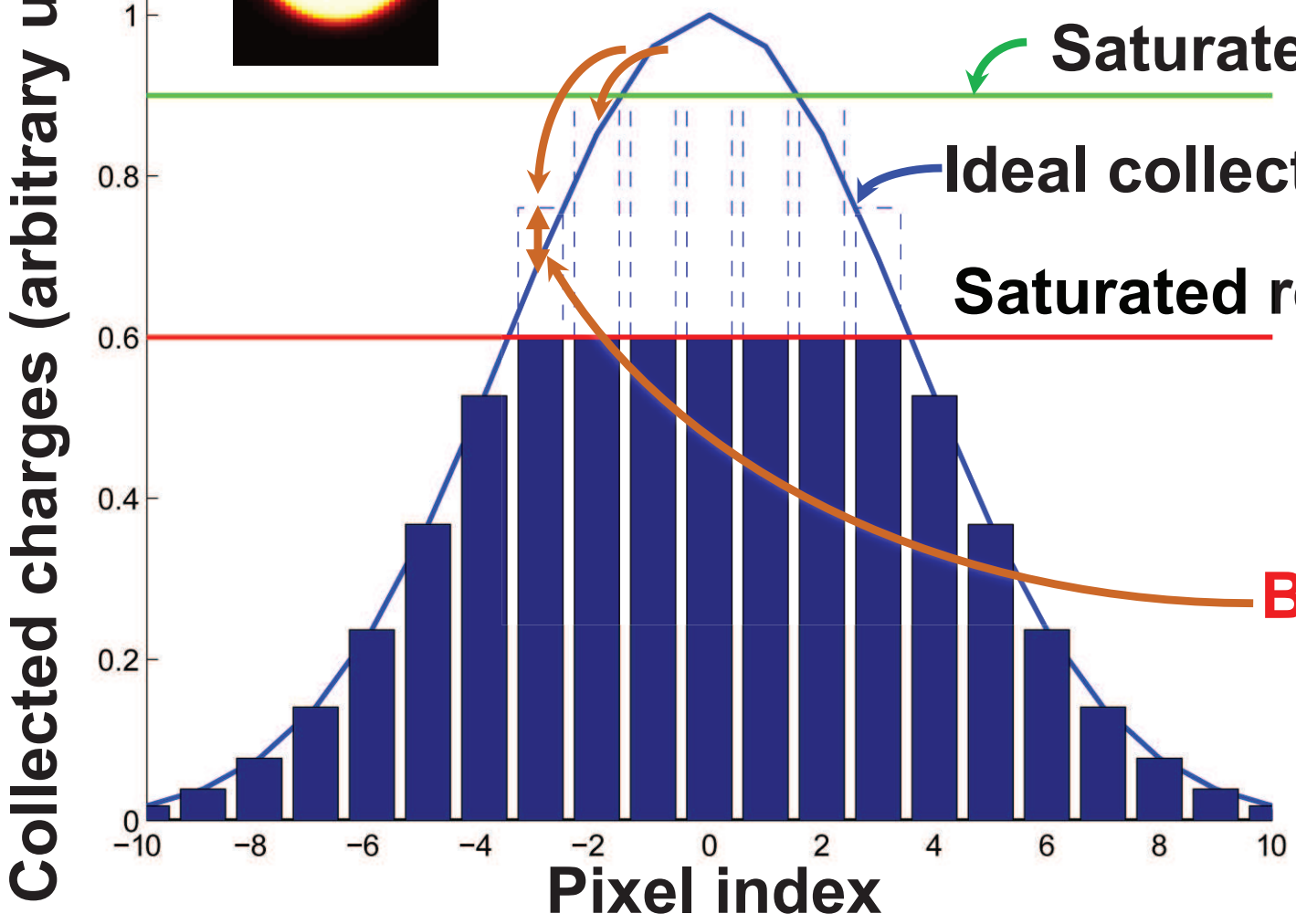
X-Cut of cluster profile

Saturated photodiode level

Ideal collection (diffusion only)

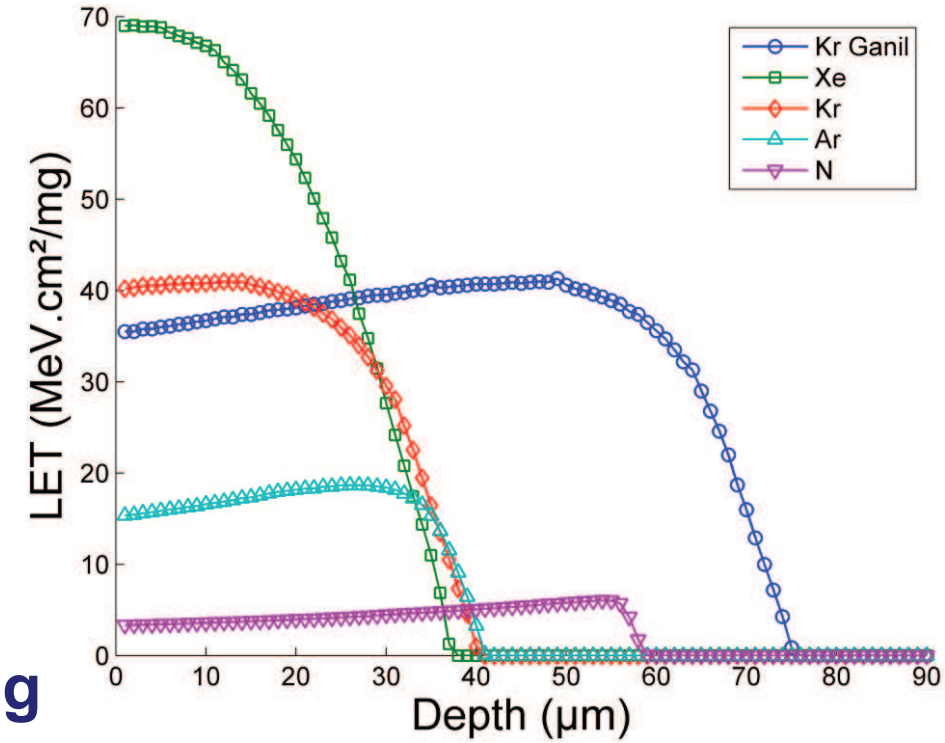
Saturated readout circuit level

Blooming is hidden on the output !



Experimental setup

- Several arrays tested
  - CMOS 0,18 µm
  - 4T PPD
  - 256 x 256 pixels
- Heavy ions : N, Ar, Kr, Xe
  - Energy : 60 to 611 MeV
  - LET : 3,3 to 67,7 MeV.cm²/mg
  - Normal Incidence
- Only the sensor area is exposed
  - Digital conversion outside the sensor
  - Frame grabbing outside the sensor



Energy deposited by each ion versus depth in Si

SEE from the imager only